CRYO-COOLED SAPPHIRE OSCILLATOR OPERATING ABOVE 35K

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Abstract

We present preliminary design features for a second generation thermomechanically compensated sapphire resonator. Developed a few years ago, the "77K CSO" resonator showed a quality factor $Q = 2\times10^6$ at an operating temperature of 85K, enabling a frequency stability of $\delta f/f < 1\times10^{-13}$. The new design promises a frequency stability of parts in 10^{15} with cooling provided by a cryocooler consuming several hundred watts or less. Optimization of the resonator design for a temperature of 40K results in a mechanical tuning rate requirement (MHz/micron) reduced by a factor of 8, allowing for reduced EM fields at the surface of the sapphire and reduced sensitivity to mechanical deformation. This optimized EM design is implemented in a self-assembling mechanical design that allows easy disassembly for cleaning, together with a first-order cancellation for expected mechanisms of physical creep. The new design is expected to share the very short thermal time constants characteristic of the 10K and 77K CSO resonators, thus allowing effective compensation of rapid temperature fluctuations.

Introduction

An important new ultra-stable oscillator technology is promised by the very high inherent quality factor of whispering gallery sapphire resonators at temperatures achievable by the use of single-stage cryocoolers [1-4]. With quality factors $Q \geq 10^8$ at temperatures above 35K, such a resonator could support an oscillator with frequency stability better than $\delta f/f \leq 3\times10^{-15}$ with cooling provided by a small single-stage Stirling or pulse-tube cryocooler. However, thermal fluctuations, together with a very substantial variation of sapphire's dielectric constant with temperature limit stability to much lower levels. If the thermal variations could be effectively cancelled or compensated, the inherent promise of the sapphire resonators could be realized. The technical challenge is to provide a relatively quick compensation process without impairing the quality factor of the resonator, and without otherwise limiting its stability.

The 10K CSO is presently the only available continuously operating short-term frequency source with ultra-high stability [5,6,7]. A smaller cryocooled oscillator with short-term stability of 1×10^{-14} or better (1 second $\leq \tau \leq$ 1000 seconds) at easily reached cryogenic temperatures represents a break-through technology. Mated with JPL's LITS trapped ion standards, a 40K CSO would offer inexpensive long-term operation and replacement of hydrogen masers in NASA's Deep Space Network (DSN) [8]. It also offers the L.O. performance required by the new generation of laser-cooled frequency standards. With a cryocooler drawing 100-300 W, a 40K CSO can provide a needed performance with much lower cost and power than previously available for both ground and flight capabilities. This compares to 5kW required by the 10K CSO cryocooler [5].

A short-term oscillator with 10^{-14} stability offers the DSN nearly all of the performance advantages of the 10K CSO with much cost and upkeep. In particular, short term performance is 10 times better than the present hydrogen masers, and 5 times better than near-term spacecraft USO performance. Additionally, this performance is an ideal mate as L.O. to the JPL LITS/LITE ion standards, enabling their inherent performance.

Background

Figure 1 shows frequency stabilities and operating temperatures for previously demonstrated short-term frequency standard technologies with stabilities of 1×10^{-13} or better. The graph shows a very large gap between the ultra-high stability available from very low temperature ($T \leq 10K$), oscillators and the approximately 1×10^{-13} stability available at more easily reached temperatures. It also outlines a region of presently needed capability with stability better than 1×10^{-14} while using the cooling available from single stage

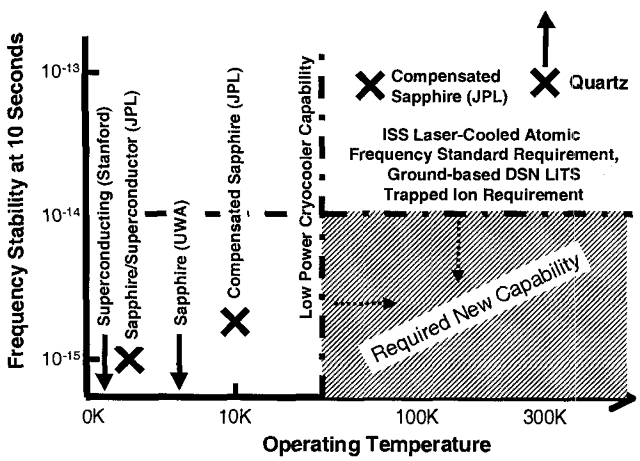

Figure 1 Scatter plot of short-term frequency standard capabilities below 10^{-13}.

cryocoolers. Of the capabilities shown, those at 10K and higher represent continuously operable frequency standards, with cooling provided by available cryocoolers.

While the short thermal time constants of sapphire and other materials in this temperature range give rise to a host of possible compensating methodologies, a primary difficulty so far has proven to be in finding a mechanism with sufficiently low loss that sapphire's quality factor is not degraded. This problem becomes progressively more severe with increasing temperature due to a T^4 dependence for sapphire's dielectric constant. Additionally, severe constraints are placed on any mechanical motion, such as those that might be due to external vibrations or internal creep and on internal thermal time constants.

A number of promising compensated sapphire resonator technologies have already been demonstrated. These include the following:

- Thermomechanical, for a $Q \approx 2\times10^6$ at 85K and a frequency stability of 8×10^{-14} [1,2].
- Dielectrics, such as Rutile, showing compensated Q's up to 10^7 at 65K [3,4].
- Paramagnetic impurities;
  - Incidental impurity compensation for $Q > 10^9$, $T \leq$ 6K and stability better than 10^{-15} [9].
  - External ruby compensation with $Q > 10^9$ below 10K and stability of 2×10^{-15} [10].

So far, these efforts fall short of reaching the needed capability in one way or another. For example, cryocoolers for the "10K CSO" frequency standards with external ruby compensation dissipate 5kW of line power, and substantially add to the size and expense of operation. Oscillators with compensation by thermal expansion have so far showed a relatively low quality factor of 2×10^6, and large frequency drift of $\delta f/f = 10^{-8}$/day, precluding long-term frequency locking to an external source.

Figure 2 illustrates two methods to bridge the gap between the capabilities of two previously developed JPL-developed

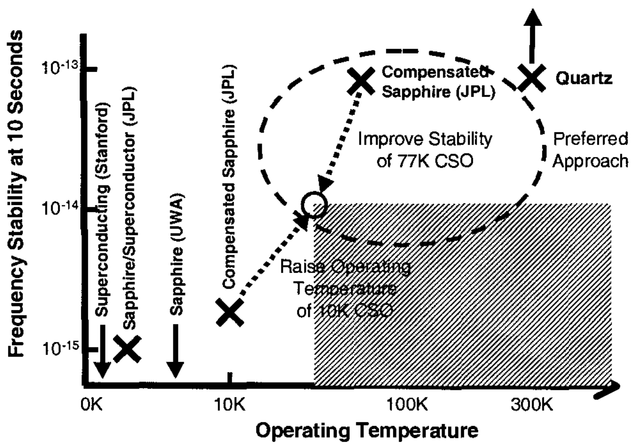

Figure 2 Approaches to the needed capability based on demonstrated compensated sapphire technologies

technologies--the 10K CSO and the 77K CSO. The 10K CSO, presently being implemented in the DSN for the Cassini Ka-band experiment, represents the first cryogenic oscillator to provide ultra-high short term stability together with long-term cryocooled operation. It provides a frequency stability of 2-4 parts in 10^{15} at measuring times (1 second $\leq \tau \leq$ 1000 seconds) without the use of liquid helium and the frequent maintenance required by previous technologies. With a short term stability 25× better than the hydrogen maser, the 10K CSO is making possible a significant upgrade of DSN frequency stability as required by the Cassini Ka-band experiment. The technology of the 10K CSO was based on our previously developed 77K CSO, which showed a stability of 8×10^{-14} with a Q of 2 million. We now propose to infuse what has been learned during the 10K development into a second generation thermomechanically compensated CSO.

Resonator Design

We identify general design requirements for a compensated sapphire resonator to achieve parts in 10^{-15} stability as:

1) Quality factor of 4×10^7 or greater
2) Drift rate of 1×10^{-16}/second or less
3) Thermal time constants of 3 seconds or less coupled with an appropriate external time constant
4) Acceleration sensitivity of 10^{-9}/g or less.

Table 1 Requirements vs 77K CSO capability

77K CSO	Need Now	How to do
$Q=2\times10^6$	$Q=4\times10^7$	♦ Post-polish anneal of sapphire parts decreases surface losses by 4× or more ♦ Optimize design for 40K – allows 8× less energy at surface ♦ Self Assembly (cleaning ease)
Drift = 1×10^{-13}/sec	Drift = 1×10^{-16}/sec	♦ Motion-canceling design ♦ Lower stress ♦ Symmetric transverse stress ♦ Lower temperature
Thermal τ = 5 sec	Thermal τ = 3 sec	♦ Utilize same general design—metal to sapphire joint inside inner caustic where RF fields are small ♦ Lower temperature gives improved thermal conductivity, reduced heat capacity
$\delta f/f = 1\times10^{8}$/g	$\delta f/f = 1\times10^{-9}$/g	♦ Center—mount resonator design

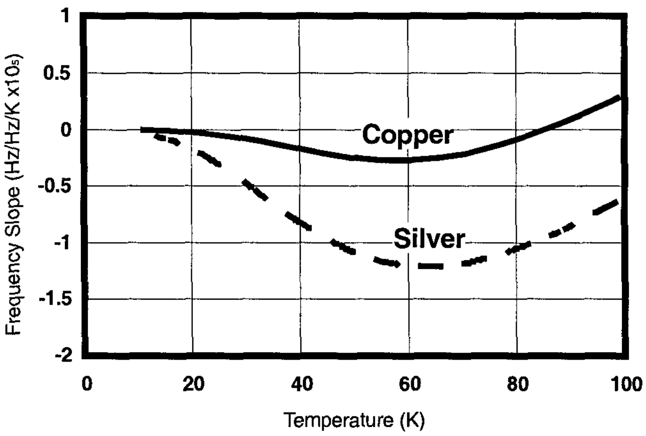

Figure 3 A high tuning rate of 66 MHz/micron enabled a turnover of 85K with a copper spacer and WGH mode orientation in the "77K CSO"

Table 1 shows a comparison of these requirements with capabilities actually achieved in the previous design. It is clear the primary challenge for a new design is to increase resonator quality factor and reduce frequency drift rate and that a strength of the previous design was the low thermal time constant.

An intermediate figure of merit of considerable import is the required mechanical tuning rate for the electromagnetic resonator, typically measured in MHz/micron. A challenge for the original design was to achieve a large 66MHz/micron tuning rate required for compensation at temperatures above 77K, while using only materials (copper, sapphire) with excellent thermal properties in this temperature range (see Fig. 3). This requirement is considerably relaxed in the new design. Lower values for the mechanical tuning rate allow smaller surface electrical fields in the resonator for reduced surface losses, a more open resonator design, and reduced sensitivity to all types of mechanical deformation.

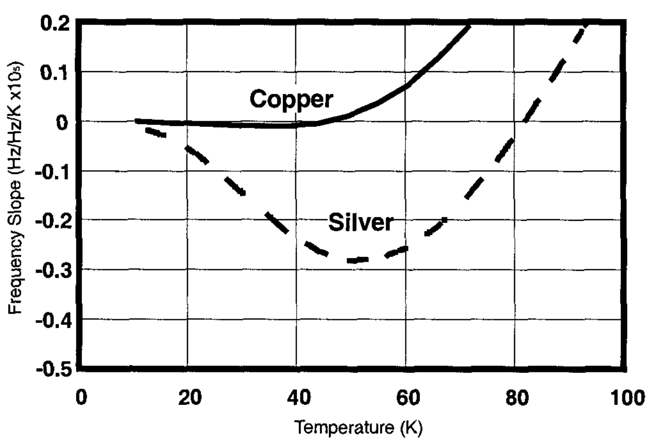

Figure 4 Use of WGE mode and a 2.84× lower tuning rate gives a turnover of 45K for the copper spacer, together with nearly complete compensation at lower temperatures; a silver spacer would show an 82K turnover.

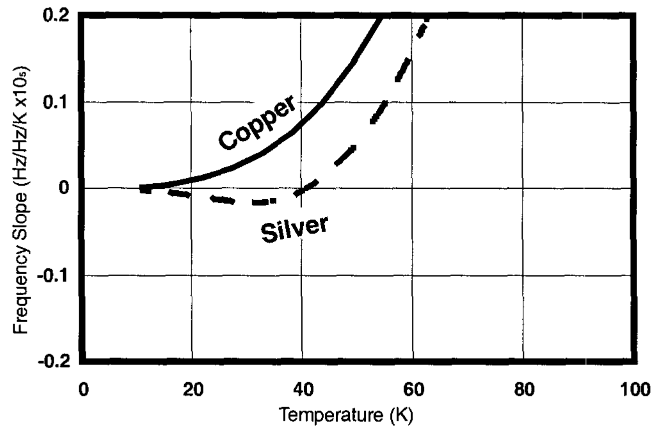

Figure 5 Optimization for a turnover at 40K with a silver spacer and WGE mode is achieved by reducing the tuning rate by 8.33×. Such resonator with a copper spacer would be under-compensated at all temperatures.

Figures 3-5 show a progression of calculated frequency slopes for the thermomechanically compensated oscillator. The model is based on Debye temperatures of 900K, 550K, 330K, and 225K for sapphire expansion, sapphire dielectric constant, copper and silver expansion, respectively. At the lowest temperatures, all the curves scale as T^3. Fig 6 shows frequency dependence for example WGH and WGE modes.

We have identified general technical approaches to meet these requirements as follows:

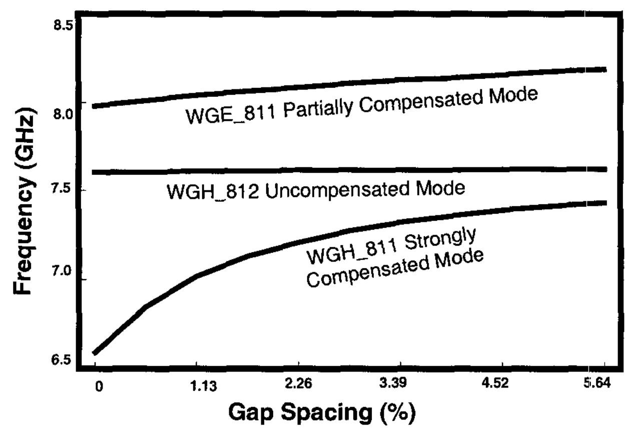

Figure 6 Finite element calculation of frequency dependence on the gap between sapphire elements for 77K CSO resonator. Lower slope requirement now allows use of WGE mode with its higher Q, lower temperature coefficient for epsilon.

- ❖ Operation at 40K instead of 85K
  - ➢ Lower temperature operation alone allows a reduction of the required mechanical tuning rate by a factor of 1.69×.
  - ➢ Lower temperature also reduces creep rates—experience with 10K CSO showed >100× reduction.
- ❖ Further optimization of resonator design for 40K.
  - ➢ Metal spacer made of silver with its Debye temperature of 225K gives larger thermal expansion rate at low temperatures compared to copper at 330K—reduce tuning rate by 2.93×.
  - ➢ Use of WGE mode with its reduced sapphire dielectric thermal sensitivity further reduces tuning rate by 1.68×.
  - ➢ Overall reduction of tuning rate requirement is 8.33×--contributes to higher Q, reduced mechanical sensitivities by this same factor.
- ❖ Post-polish anneal of sapphire parts.
  - ➢ Experience with 10K CSO indicates that annealing reduces overall losses by 4× or more. Surface losses important to tunable resonator design may be reduced even more.
- ❖ Self-assembling mechanical design.
  - ➢ Transverse (radial) joining by differential thermal contraction on cool-down.
    - ▪ Join metal spacer to the 2 sapphire end parts.
    - ▪ Also join spacer to internal support .
  - ➢ Gravity alignment at room temperature—parts support each other but then pull away after grips take hold.
  - ➢ High hardness and precision of sapphire parts prevents groove formation, allows re-assembly.
  - ➢ Easy re-cleaning of parts.
  - ➢ Low temperature anneal after first assembly may reduce subsequent mechanical creep.
  - ➢ Reduce material stress by control of mechanical clearances--0.3 mil tolerance is required.
  - ➢ Use very short metallic contact regions to reduce sensitivity to angular misalignment upon cool-down.
    - ▪ Very long contact region would be required to prevent binding due to misalignment.
    - ▪ Short region eliminates negative consequence of slight misalignment.
- ❖ Advanced mechanical design to give first order cancellation of axial motion due to relaxation of radial stress.
  - ➢ Three axial/radial motion transfer coefficients impact frequency creep.
    - ▪ Radial relaxation of center grip of metal spacer onto sapphire post can change spacer length.
    - ▪ Radial relaxation of end grips of metal spacer onto sapphire parts can change spacer length.
    - ▪ Radial relaxation of end grips of metal spacer onto sapphire parts can bend sapphire.
  - ➢ Advanced mechanical design can adjust each of these to give nominally zero axial motion due to radial relaxation of grip stress.
- ❖ Center support of the 3-part compensated resonator for reduced g—sensitivity.
  - ➢ Accurate center support should reduce acceleration sensitivity by 100× or more.
  - ➢ Previous design used end support.
- ❖ Thermal contact between elements by metal to sapphire joint in low RF field region of resonator.
  - ➢ Region inside inner caustic has very low RF fields, allows use of metallic parts
  - ➢ Use of soft metals, possible gold-plating on metal spacer improves improve thermal contact

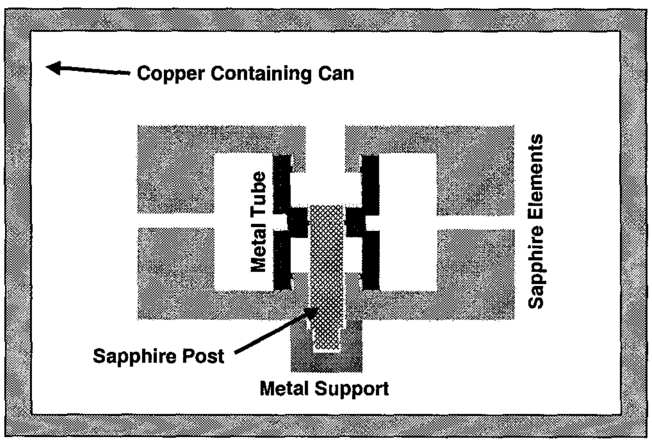

Figure 7 Cylindrical cross section of self-assembling resonator design. Upon cool-down, thermal contraction causes metal spacer and support to grip sapphire parts and then retract from other contacts.

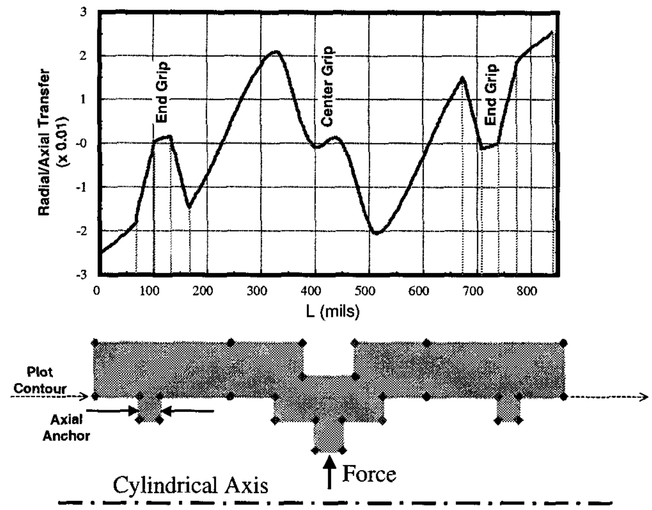

Figure 8 Motion-canceling designs eliminate axial motion and associated frequency creep when force at either center grip or end grips relaxes with time. This example shows nominally zero motion of end grips due to force on center grip of metal spacer.

- Previous designs used indium-sapphire joint to achieve 5 second thermal time constant at 77K, 1second at 10K. However, ultra-soft indium seems a likely candidate as source for mechanical creep and is not being considered here.

Figure 7 shows a cross section view of the mechanical resonator design. Fig. 8 shows the results of finite element calculation of axial motion in response to radial force at the center grip for a preliminary design candidate. One half of the cylindrical cross section is shown, rotated 90 degrees from Fig. 7.. A similar finite element calculation is used to adjust end grip positions so as to eliminate any axial motion induced by radial creep at the end grips.

Conclusion/Acknowledgment

We have presented preliminary design features for a second-generation thermomechanically compensated sapphire resonator optimized for operation near 40K. This development builds on JPL capabilities demonstrated in the successful development of the 10K and 77K CSO's, short term frequency standards which achieve stability in the 10^{-14}'s and 10^{-15}'s without the use of liquid helium. This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

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